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A statistical approach to estimating runoff in center pivot irrigation with crust conditions

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Abstract

There have been several proposals to evaluate potential runoff in center pivot irrigation, through the integration of time varying infiltration–precipitation rate curves, involving complex iterative procedures. Some methods use empirical infiltration functions, such as the Kostiakov equation. Others use physically based infiltration functions, such as the Green–Ampt equation. Another option is to use the Richards equation, describing the one-dimensional vertical infiltration of water into the soil for a specified irrigation event. This equation is generally accepted to provide a basis for comparison between other runoff estimation methods.

[P.B. Luz, J.C. Martins, M.C. Gonçalves, Reliable estimate of runoff in center pivot irrigation: statistical approach, in: Proceedings of the 16 Congress Mondial de Science du Sol, Poster 2-658, ISSS, Montpellier, France, August 19–25, 1998, pp. 577–593], developed a conceptual method of statistical nature, to estimate potential runoff in center pivot irrigation, comprising regression equations built with runoff results from a simulation computer model using the Richards equation. The procedure to simulate runoff involved a wide set of data related to water retention parameters and soil texture [W.J. Rawls, D.L. Brakensiek, Estimation of soil water retention and hydraulic properties, in: H.J. Morel-Seytoux (Ed.), Unsaturated Flow in Hydrologic Modeling, Theory and Practice, Kluwer Academic Publishers, Dordrecht, 1989, pp. 275–300], and water application. Such regression equations present a dependent variable, defined as an index of four parameters, related to the center pivot irrigation and to the soil-water system evaluation. The method had unacceptable results when a crust developed on the soil surface. Therefore, the objective of this study was to redefine the index,

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establishing new parameter coefficients with a trial and error approach. The model efficiency (similar to the coefficient of determination, r^2) ranged from 90 to 98%, showing the results are in good agreement to those computed by Richards equation, exhibiting a strong predictive value.

Keywords: Runoff; Center pivot; Statistics; Infiltration models; Surface crust

1. Introduction

Runoff control is an important factor in the successful design and operation of a center pivot irrigation system. Runoff is most likely to occur with high application rates, typical of popular developed low pressure systems, and where soils have a low intake rate.

Estimation of potential runoff generally demands an iterative numerical calculation relating an infiltration function to a center pivot precipitation pattern. Some authors base their runoff models on the empirical Kostiakov infiltration equation (Kincaid et al., 1969), or on physically based infiltration functions such as the Green–Ampt equation (Slack, 1980; von Bernuth, 1982). In current runoff approaches, mainly when integrated in irrigation conceptual models (Wilmes et al., 1993; Kincaid, 2001), many authors still utilize the referenced equations. As far as those equations and the Richards equation are in agreement, they assume that the infiltration capacity can be approximated as a simple function of cumulative infiltration regardless of the application rate versus time history (Skaggs et al., 1983). The Richards equation, for describing the one-dimensional vertical infiltration of water into soil, is a useful tool to provide a data-base for comparisons between runoff simulation models. Therefore, soil samples, many times presenting a large degree of spatial and temporal variability, are not needed.

Luz et al. (1998) developed a simple statistical method to estimate potential runoff based on the theoretical results derived by numerical solution of the Richards equation, for vertical water infiltration into soil. Soil hydraulic properties used as input data to the Richards equation were estimated using equations from Rawls and Brakensiek (1989). Initial procedures to build regression equations comprised a selection of the main parameters with impact on runoff. The objective was to avoid very large and complex equations, thus parameters with small impact on infiltration were not included. The evaluations from several studies, reported by Risse et al. (1994), pointed to precipitation (amount and rate) and hydraulic conductivity as the parameters with major impact on infiltration and runoff. The final statistical solution includes three linear regression equations, each for a defined soil-sand percent class. The parameters, within the independent variable, are related to the center pivot design, the irrigation management, the soil hydraulic characterization, and the initial soil water. This procedure provides a fast and reasonably accurate result using basic functions with a small hand held calculator.

Field tests data for validating the runoff statistical model clearly showed that soil crusts were present. This factor may cause a determinant reduction on the infiltration rate by up to 80% (Moore, 1981). Summer and Stewart (1992) present a detailed examination of the chemical and physical processes of soil crusting. Rawls and Brakensiek (1983), reporting relationships of crust saturated hydraulic conductivity, state that, in most cases, soil crusting is characterized with a modified infiltration equation and parameters related to the hydraulic properties of the soil crust and subcrust. In center pivot irrigation, Luz et al. (1997), observed runoff from 0 to 25% of the water application where minimum tillage was the selected soil conservation practice and no crust was formed. In ploughed silt loamy soils runoff increased up to 80% and a soil crust of 0.3 cm was observed. Dixon and Peterson (1971) developed a channel system concept of infiltration that described the profound influence of large soil pores on the movement on soil water and air. This would partially explain the differences in tillage and soil texture on infiltration. The design peak application rate and initial soil water content have a reduced affect on runoff. From field observations, Luz et al. (1998) suggested some changes in the statistical model, in order to decrease the weight of such parameters when a surface crust is formed. The objective of this study is to reformulate the linear regressions to estimate runoff with soil crust conditions. A sensitivity analysis on alternative values of the parameters in the independent variable was performed to modify the statistical model for crust conditions.

2. Procedures

The development of the statistical runoff model for crust conditions, involve several models, methodologies and assumptions presented here.

2.1. Numerical solution of Richards equation – GNFLUX (Smith, 1992)

The statistical model was developed by using a computer program – GNFLUX (Smith, 1992), to simulate the vertical water infiltration into soil and the potential runoff for a given soil location. The program numerically solves the Richards equation. The following steps are used to generate the input required for the program.

The soil hydraulic properties required as program input data are estimated from regression equations (Rawls and Brakensiek, 1983), which relate the Brooks and Corey (1964) parameters: porosity (Φ), saturated hydraulic conductivity (K_s), residual water content (θ_r), pore size distribution index (λ) and bubbling pressure (h_b), to soil texture and other soil properties. These regressions were based on analysis of 1323 soils in the US. The inputs to the program for the water content-matric potential and the hydraulic conductivity relationships, use a shift factor equal to 2 in the hysteric soil simulation (in some models it is not considered), and a curvature coefficient equal to 5, related to the parameter representing the air entry potential (as in the OPUS integrated simulation program (Smith, 1992)). To run the GNFLUX it is also necessary, for the given soil location, to set the initial soil water content (volume data) for a specific soil depth, the peak application rate and the water application time. These two water application parameters are needed to define the water application depth with the assumed parabolic application rate pattern.

2.2. Runoff statistical model (RSM) (Luz et al., 1998)

Runoff data simulated with the GNFLUX program for 23 data points were used to build the statistical model. Brooks and Corey retention parameters (observed in graphical mode)

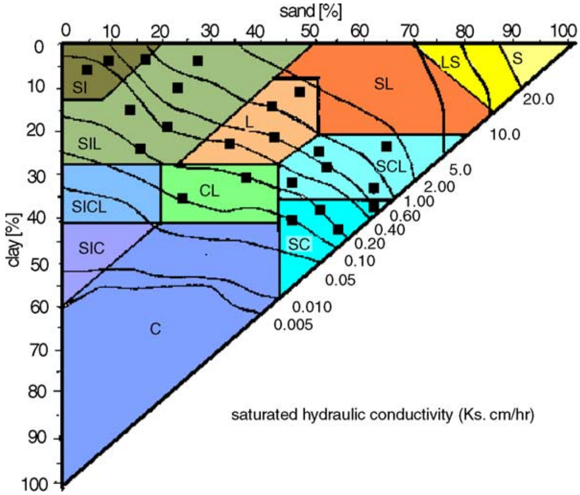

Fig. 1. Brooks–Corey water retention parameters: K_s.

for soils with 1.5% organic matter, and a wide range of soils with 5–65% of sand and 5–45% of clay were used to generate the 23 data points. As an example, the values of K_s are presented in Fig. 1.

The selected soils for the 23 points, are reported to have K_s ranging from 0.1 to 2 cm/h. This selected range is representative of most irrigated soils where we are interested in controlling runoff from a center pivot system.

For these 23 soil options, the GNFLUX program was run for different combination of water application rate, time and initial soil water. Peak application rates of 3.5, 6 and 10 cm/h, were used representing typical high, medium and low pressure systems; application times were determined for five target application depths: 7, 14, 21, 28 and 35 mm; while initial soil water content values were: 18, 26, 32 and 36%, by volume. The relationship between the water application rate through time may be described by a geometric pattern. Therefore, choosing an elliptical, parabolic or triangular pattern (Fig. 2), the water application time can be calculated for the assumed peak application rate and application depth. The parabolic pattern was selected and was assumed to be representative of center pivot precipitation. This pattern for the same water application depth and time has a peak rate between the elliptical and triangular patterns. The selection of the initial soil water content is related to typical irrigated soil conditions, where the soil water is above the wilting point and below saturation, to avoid crop water stress or water losses through the profile, respectively. With the 23 soils selected, it was possible to estimate over 1300 potential runoff values.

The runoff statistical model, assuming non-crusting soil conditions, was developed with a step-wise technique. A multiple regression using the potential runoff (PR) data set from the numerical solution of Richards equation provided a first estimation of the parameters. Soil parameters with the greatest impact on estimated infiltration were the saturated hydraulic conductivity (K_s), the porosity (Φ) and the bubbling pressure (h_b).

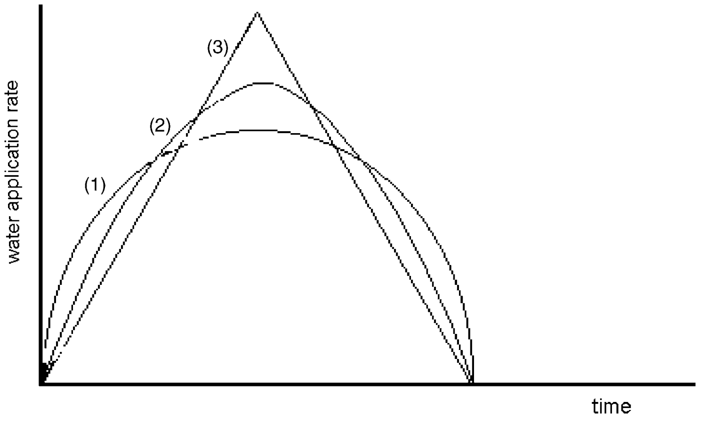

Fig. 2. Precipitation patterns: (1) elliptical; (2) parabolic; (3) triangular.

In further statistical procedures, to define a more simplified model, it was found that h_b could be removed due to its co-linearity with K_s and also Φ could be removed due to the small range of typical soils (between 40 and 50%). By trial and error, the conceptual model resulted with three different linear regression equations for soil-sand percent ranges. These equations and the multiple-regression indicated a similar goodness of fit, but the advantage of fewer parameters and less complexity lead to the selection of the linear equations.

Such equations presented an index, with parameters and respective coefficients established from attempts of the step-wise initial procedure. The index, X, was defined as

$$X = \left(\frac{P_k H}{K_s}\right)^{0.5} D \quad (1)$$

with the following parameters:

- peak of precipitation (P_k in cm/h);
- water depth (D in cm);
- initial soil water content (H in vol.%);
- saturated hydraulic conductivity (K_s in cm/h).

And the linear regressions (Fig. 3), to represent potential runoff, PR, in mm, were

- soils R1 (% sand: 0–39)

$$\mathrm{PR} = 1.7X - 5.0 \quad (2)$$

- soils R2 (% sand: 40–50)

$$\mathrm{PR} = 2.1X - 3.0 \quad (3)$$

- soils R3 (% sand: 51–100)

$$\mathrm{PR} = 2.8X - 1.8 \quad (4)$$

The coefficient of determination (r^2) ranged from 87.2 to 88% for these regressions.

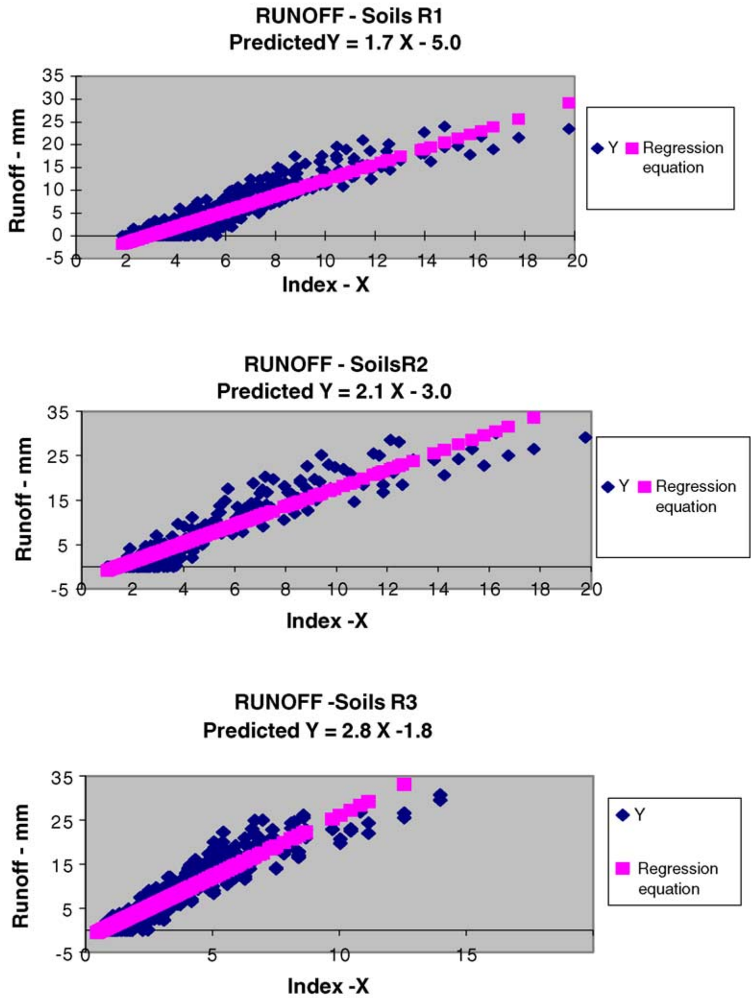

Fig. 3. Graphical form of linear regressions. Observed Y = runoff values from Richards equation.

2.3. Model efficiency (Nash and Sutcliffe, 1970)

The Nash and Sutcliffe model efficiency was applied to indicate the agreement between the ‘‘measured’’ (from Richards equation) and predicted values (from the runoff statistical model (RSM)). This concept, which is similar to the correlation coefficient from linear regression, r^2, is defined as

$$E = 1 - \frac{\sum_{t=1}^{n}(Y_t - P_t)^2}{\sum_{t=1}^{n}(Y_t - \bar{Y})^2} \tag{5}$$

where E is the model efficiency, Y_t and P_t the observed and predicted output for event t, respectively, and $\bar{Y}$ is the average of the observed values.

An important difference between the model efficiency and r^2 values is that the model efficiency compares the predicted values to the 1:1 line between measured and predicted values rather than the best regression line through the points. The model efficiency will always be lower than the correlation coefficient and the amount by which it is lower is indicative of a bias in the model. When the model efficiency is negative it indicates that the average output value is a better estimate than the model prediction (Risse et al., 1994).

2.4. Soil crust conductivity model (Brakensiek and Rawls, 1983)

The final saturated hydraulic conductivity of a crust may be estimated from a steady-state relationship modified by Brakensiek and Rawls (1983) as

$$K_{\mathrm{SC}} = \frac{Z_{\mathrm{c}}}{h_{\mathrm{I}} + Z_{\mathrm{c}}}(\mathrm{SC})(K_{\mathrm{sat}}) \tag{6}$$

where Z_c (cm) is the crust thickness, h_I the steady-state capillary suction increase at the crust/subcrust interface (Table 1), SC the correction factor for partial saturation of the subcrust soil (Table 1) and K_{sat} (cm/h) is the saturated subcrust conductivity. The application of this equation is accepted if the crust has a stable K_{SC} value which happens usually after about 50 mm of cumulative precipitation (or after one or more irrigations). Even though the modified surface may be quite thin, between 0.1 and 1 cm, the crust development decreases both the infiltration volume and the infiltration rates (Moore, 1981). Some models take into account the crust sealing affect on runoff prediction. OPUS (Smith, 1992), assumes a value of 1 cm, other studies proposed by Moore (1981) and Brakensiek and Rawls (1983) assume 0.5 cm.

It may also be assumed that surface sealing changes only the saturated hydraulic conductivity and not the saturated water content or the soil water retention curve (Moore (1981). Although Edwards (1967) has shown that this assumption is not strictly correct, it should be a reasonable first approximation that will permit examining the effect of surface

Table 1
Mean steady state matric potential drop, h_I, across surface seals by soil texture (Rawls and Brakensiek, 1989)

Soil texture	Matric potential drop (h_I) (cm)	Reduction factor for subcrust conductivity (SC)
Sand	2	0.91
Loamy sand	3	0.89
Sandy loam	6	0.86
Loam	7	0.82
Silt loam	10	0.81
Sandy clay loam	5	0.85
Clay loam	8	0.82
Silty clay loam	10	0.76
Sandy clay	6	0.80
Silty clay	11	0.73
Clay	9	0.75

sealing on infiltration. On the other hand, predicted runoff may be indistinctly related to bare soil or to soil with a maize crop. According to field research of Luz et al. (1997) and Ghidey and Alberts (1994), the differences between such conditions are not statistically significant for the case of maize.

2.5. Parameters for soil crust model

The objective of this study is to redefine the index X (Eq. (1)), for soil crust conditions. Each parameter of the index X, was examined to determine needed changes in exponents for the statistical model (RSM) to estimate the potential runoff as calculated by the Richards equation for soil crust conditions. The changes were evaluated by three criteria: average runoff, coefficient of determination (r^2) and slope, of the RSM, when plotted versus the individual Richards equation simulation, for solution of statistical model. The procedure is an adaption of that presented by Risse et al. (1994). The coefficient C_i is a multiplier to the index X, to have the trends (regression lines) of the Richards simulations and statistical model to be very close to each other over the entire range. The average runoff from the two methods is nearly equal with this adjustment.

The exponents of each of the parameters in the index, X, were independently iterated between the limits of 0.1 and 1.5 with the final selection based on the three criteria. After each of the exponents was independently evaluated, the final C_i was determined. Table 3 illustrates the result of the trial and error procedure for each of the soil and hydraulic conductivity divisions. The results were adjusted to be an adequate approximation for estimating potential runoff with soil crust conditions

3. Results and discussion

According to charts and Table 1 proposed by Rawls and Brakensiek (1989), Brooks–Corey water retention parameters were taken from Table 2 as soil input parameters to solve the numerical solution of the Richards equation (GNFLUX program). A total of 21 soils were for simulated, comprising 17 (5 R1, 6 R2 and 6 R3 soils) for assumed theoretical soil conditions, plus 4 for data collected from field research plots (R1-4, R2-4, R3-4, R3-5). These were selected (Table 2) to redefine the index, X, to allow the RSM to reflect crust conditions. It should be noted that results from the R3-4 and R3-5 field soil plots had much smaller clay percentages than the first three R3 typical theoretical data. The assumed theoretical soil condition, R3-8 had similar clay percentages but the expected K_s is 2.60 cm/h as compared to a measured value of near 0.80 from field plots R3-4 and R3-5.

Potential runoff results from GNFLUX were simulated for a total of 252 cases. The following data were run with GNFLUX: peak application rate (the parabolic precipitation pattern was assumed) at 3, 4, 7 and 10 cm/h; water application time, limited by selected water depth levels of 10, 17, 20, 24, 30 and 34 mm; for each peak rate, initial soil water content varied from 10 to 30 vol.%. The K_s ranged from 0.1 to 2.6 cm/h and the application of the soil crust conductivity model led to K_{SC} values ranging from 0.0022 to 0.11 cm/h, which means conductivity ratios (K_s/K_{SC}) ranging from 50 for clay soils, to 25 for sandy

Table 2
Parameters from estimation equations and soil crust parameters (Brooks and Corey, 1964)

Soils	Sand (%)	Clay (%)	K_{sat} (cm/h)	Φ (%)	θ_r (%)	h_b (cm)	λ index	h_I (cm)	SC index	K_{SC} (cm/h)
R1-1	10	27	0.10	53	6	70	0.250	10	0.76	0.0022
R1-2	20	20	0.40	55	6	43	0.275	11	0.73	0.0078
R1-3	**25**	**18**	**0.50**	**55**	**6**	**38**	**0.280**	**11**	**0.73**	**0.010**
R1-4[a]	34	23	0.51	45	1	35	0.145	10	0.81	0.012
R1-5	30	8	1.00	57	4	30	0.315	11	0.73	0.019
R1-6	35	5	1.50	57	3	25	0.325	11	0.73	0.029
R2-1	42	34	0.20	47	9	38	0.200	8	0.82	0.0059
R2-2	41	28	0.35	49	8	35	0.220	8	0.82	0.010
R2-3	42	25	0.50	48	6	32	0.240	7	0.82	0.017
R2-4[a]	**42**	**20**	**0.50**	**45**	**1**	**30**	**0.157**	**7**	**0.82**	**0.018**
R2-5	44	23	0.60	48	7	28	0.250	7	0.82	0.020
R2-6	45	15	1.00	51	6	25	0.280	7	0.82	0.034
R2-7	45	10	1.80	52	4	24	0.300	7	0.82	0.061
R3-1	52	40	0.20	45	8	30	0.150	6	0.80	0.0076
R3-2	55	40	0.25	45	8	29	0.150	6	0.80	0.010
R3-3	56	34	0.50	44	9	19	0.190	5	0.85	0.024
R3-4[a]	64	12	0.79	38	1	12	0.176	6	0.86	0.032
R3-5[a]	65	10	0.88	38	1	13	0.192	6	0.86	0.036
R3-6	**65**	**33**	**1.00**	**43**	**9**	**14**	**0.200**	**5**	**0.85**	**0.048**
R3-7	60	20	1.60	46	8	15	0.250	6	0.86	0.066
R3-8	65	12	2.60	48	6	12	0.275	6	0.86	0.110

Bold values indicate spliting regression equations groups.
[a] Values adopted from field plots.

soils. The soil surface crust layer, based on field measurements of silty-loam soils was assumed to be 0.3 cm

One objective of the simulation, with soil crust conditions, was to maintain the same groups of soils (R1–R3) and the same regression coefficients. The main objective was to check and modify the impact of each parameter within the index *X*. The exponent of the parameters in the runoff statistical model (Table 3) was adjusted to have agreement with the potential runoff data from the Richards equation. Another way could be, according to crust conditions, to use runoff rates simulated by the Richards equation to generate a new set of regressions, with the advantage of maintaining the index, *X*. However, this option leads to new R1–R3 soil texture ranges. Thus, it would be not possible to keep the original set of three ranges, as a tool to a direct observation of runoff simulation with RSM, for any soil condition.

The first attempts to define new exponents in the index parameters, led to dividing each soil group, in order to attain a stronger regression goodness of fit, for lower and higher soil saturated conductivities. Conceptually, we assumed soils R1 and R2 to be divided at K_s of 0.5 cm/h and a soil R3 divided at 1 cm/h. The soil crust conductivity, K_{SC}, had values of 0.010, 0.017 and 0.048 cm/h, for soils R1–R3, respectively.

Each parameter exponent was changed for the model simulation while the others were maintained as in the original model index (no crust conditions). For example, the exponent for P_k was varied from 0.1 to 1.5, while the other exponents remained at one in the first trial

Table 3
Sensitive analysis of parameters, comparing the runoff statistical model (RSM), with a modified parameter, to Richards equation, checking slope, average runoff and the coefficient of determination, r^2 (only initial and best coefficients are presented)

Parameter	$K_s > 0.5$					$K_s < 0.5$				
	Coefficient		RSM		r^2	Coefficient		RSM		r^2
	c	C_i [a]	Slope	Average runoff (mm)		c	C_i [a]	Slope	Average runoff (mm)	
Soil group R1										
P_k^c	1.0	2.5	0.14	6.17	0.81	1.0	3.0	−0.57	12.75	0.75
	0.8	2.0	0.14	6.71	0.78	0.5	2.5	−0.47	8.64	0.72
H^c	1.0	2.5	0.14	6.17	0.81	1.0	3.0	−0.57	12.75	0.75
	0.10	4.5	0.15	7.14	0.90	0.10	6.0	−0.52	12.42	0.80
K_{SC}^c	1.0	2.5	0.14	6.17	0.81	1.0	3.0	−0.57	12.75	0.75
	0.7	1.0	0.13	10.05	0.81	0.3	0.5	−0.11	11.61	0.87
D^c	1.0	2.5	0.14	6.17	0.81	1.0	3.0	−0.57	12.75	0.75
	0.7	2.0	0.14	6.43	0.80	0.8	3.0	−0.50	10.36	0.67
Richards			0.10	8.70				−0.13	13.27	
Soil group R2										
P_k^c	1.0	2.5	0.14	6.76	0.75	1.0	3.0	0.41	11.61	0.86
	1.4	3.5	0.14	6.96	0.81	0.6	2.0	0.40	12.08	0.86
H^c	1.0	2.5	0.14	6.76	0.75	1.0	3.0	0.41	11.61	0.86
	0.40	3.5	0.16	7.96	0.81	0.10	6.0	0.42	11.53	0.87
K_{SC}^c	1.0	2.5	0.14	6.76	0.75	1.0	3.0	0.41	11.61	0.86
	1.4	4.5	0.23	8.14	0.80	0.2	0.5	0.16	10.86	0.89
D^c	1.0	2.5	0.14	6.76	0.75	1.0	3.0	0.41	11.61	0.86
	0.7	2.0	0.16	7.14	0.81	0.7	2.5	0.36	11.26	0.80
Richards			0.25	7.21				0.16	12.21	

	$K_s > 1.0$					$K_s < 1.0$				
	Coefficient		RSM		r^2	Coefficient		RSM		r^2
	c	C_i [a]	Slope	Average runoff (mm)		c	C_i [a]	Slope	Average runoff (mm)	
Soil group R3										
P_k^c	1.0	2.5	0.07	6.86	0.89	1.0	3.0	0.31	11.25	0.71
	1.5	4.0	0.07	6.73	0.91	0.7	2.5	0.28	10.07	0.71
H^c	1.0	2.5	0.07	6.86	0.89	1.0	3.0	0.31	11.25	0.71
	0.50	3.5	0.06	7.37	0.89	0.15	4.0	0.27	11.07	0.75
K_{SC}^c	1.0	2.5	0.07	6.86	0.89	1.0	3.0	0.31	11.25	0.71
	1.5	5.0	0.10	6.63	0.89	0.3	0.5	0.12	8.42	0.91
D^c	1.0	2.5	0.07	6.86	0.89	1.0	3.0	0.31	11.25	0.71
	0.9	2.5	0.07	6.25	0.89	0.9	3.0	0.29	10.27	0.69
Richards			0.07	6.71				0.09	12.32	

[a] C_i value is applied to X index (Table 4) to reduce bias of slope and average runoff of RSM. r^2 result is not affected by C_i value (the model of efficiency would be and the difference would be the bias, but the interest of studying the impact of a modified parameter is to check trends of such modified equations).

Table 4
Equations to estimate potential runoff (PR) with statistical model

Soil	Regression	Conditions	Index X
R1	PR = 1.7X − 5.0	No crust	$X = (P_k H/K_s)^{0.5} D$
		Crust: $K_s > 0.5$	$X = ((P_k^{0.8} H^{0.1}/K_{SC}^{0.7})^{0.5} D^{0.7})/1.5$
		Crust: $K_s < 0.5$	$X = ((P_k^{0.5} H^{0.1}/K_{SC}^{0.3})^{0.5} D^{0.8})/0.5$
R2	PR = 2.1X − 3.0	No crust	$X = (P_k H/K_s)^{0.5} D$
		Crust: $K_s > 0.5$	$X = ((P_k^{1.4} H^{0.4}/K_{SC}^{1.4})^{0.5} D^{0.7})/9$
		Crust: $K_s < 0.5$	$X = ((P_k^{0.6} H^{0.1}/K_{SC}^{0.2})^{0.5} D^{0.7})/0.5$
R3	PR = 2.8X − 1.8	No crust	$X = (P_k H/K_s)^{0.5} D$
		Crust: $K_s > 1.0$	$X = ((P_k^{1.5} H^{0.5}/K_{SC}^{1.5})^{0.5} D^{0.9})/10.5$
		Crust: $K_s < 1.0$	$X = ((P_k^{0.7} H^{0.15}/K_{SC}^{0.3})^{0.5} D^{0.9}$

and error stage. Following this procedure, soil group R1 and $K_s > 0.5$ (Table 3), had the best trend with the P_k exponent equal to 0.8, when comparing to the Richards equation (correct) values through the evaluation criteria (average runoff, slope); however the coefficient (C_i) of the index X had to be adjusted for the model results and Richards equation values to have the closest match. With this procedure, the best P_k exponent found gave the following characterization of runoff results, which were compared to the runoff predicted by the Richards equation (Rr): average runoff, 6.71 (Rr: 8.70); slope, 0.14 (Rr: 0.14); the r^2 found was equal to 78%. The procedure was repeated for each index parameter.

The next step was to check the combination of index parameters with such exponents that had an acceptable model efficiency and *t*-test. For the example, the coefficients with bold values (Table 3) were selected, and the best C_i coefficient was found to be equal to 1.5 (Table 4). Thus, the final index equation defined for a R1 soil with crust and $K_s > 0.5$ cm/h had the same regression coefficients for the R1 soil equation (1.7 and 5.0 (Table 4)). The model efficiency for this example was 92%.

The final evaluation of new equations for soil crust conditions is presented in Table 5. The model efficiency ranged from 90 to 98% and the *t*-test: paired two sample for means,

Table 5
Potential runoff statistics of output (equations of Table 4)

Soil group	Observed	Runoff mean value (mm)		*t*-Test		r^2	Model efficiency
		RSM	Richards equation	*t*-Stat	*t*-Crit		
R1, $K_s < 0.5$	46	8.47	8.70	1.06	1.68	0.92	0.92
R1, $K_s < 0.5$	30	13.02	13.27	1.37	1.70	0.98	0.98
R2, $K_s < 0.5$	40	7.50	7.21	−1.21	1.68	0.92	0.90
R2, $K_s < 0.5$	36	12.51	12.21	−1.09	1.69	0.94	0.93
R3, $K_s < 1.0$	44	6.90	6.71	−0.83	1.68	0.93	0.93
R3, $K_s < 1.0$	56	12.50	12.32	−1.19	1.67	0.97	0.97
Total	252						

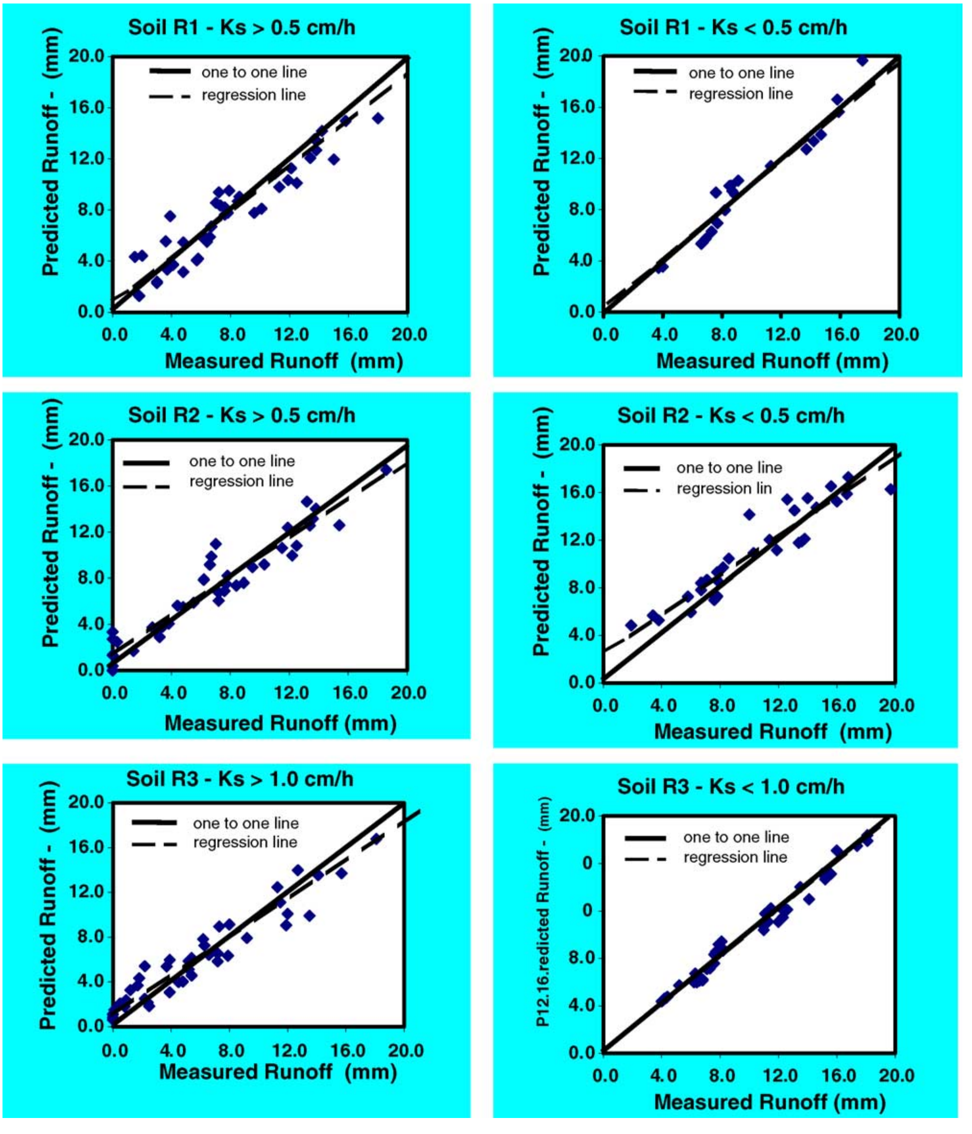

Fig. 4. Potential runoff: predicted values (from runoff statistical model) vs. "measured" values (from Richards equation), for soil crust conditions, for soil types (R1–R3) and K_s.

showed that the results from the Richards equation and from the runoff statistical model are not significantly different at the 5% level. Fig. 4 shows a good correlation of "measured" values (from Richards equation) versus predicted values (from RSM – crust conditions). Thus, the two equations exhibit a trend and are nearly of equal predictive value.

From the equations, it is clear that the parameter impact is reduced, when compared to no crusting conditions. This means that parameter increases causes a smaller change in potential runoff. The analysis of simulations also showed that both models for crusts had runoff values exceeding 80% of the water applied per irrigation.

However, the successful application of a runoff statistical equation depends obviously on the accuracy level of input parameters, which shall be preferably calibrated to field measurements, rather than estimated, based on other soil properties or system characterizations. The effects of macroporosity, cracking and other natural phenomena on infiltration behaviour shall be the topic of future research.

4. Conclusions

A conceptual statistical model (runoff statistical model (RSM)), developed to estimate potential runoff under center pivot irrigation was adapted to soil crusting conditions. This initial potential runoff model was based on a runoff data-base obtained with a numerical solution of the Richards equation. The procedures in the development of RSM, involved a sensitivity analysis and a trial and error method to change exponents for the proposed model parameters. A set of tests (slope, average and coefficient of determination) was run to quantify the effect of new coefficients. All runoff results from different stages of the procedure were compared to runoff predicted to occur by the Richards equation runoff, at the same assumed irrigation and field conditions, to achieve the best RSM equations.

Based on the model performance (higher than 90%), it can be said that the RSM and Richards equation are nearly of equal predictive value. This statement leads to the conclusion that the modified RSM can be used for field estimation of potential runoff for soils under crust conditions for center pivot sprinkler systems and is much easier for practical application than the more theoretical Richards equation.

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